Aspects of Modelling the Cleaning of a Chocolate with Yield Stress in a pipe using CFD

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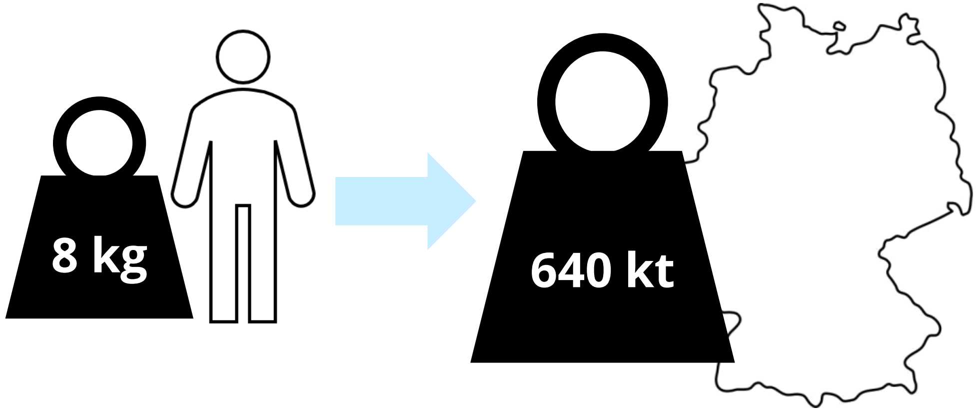
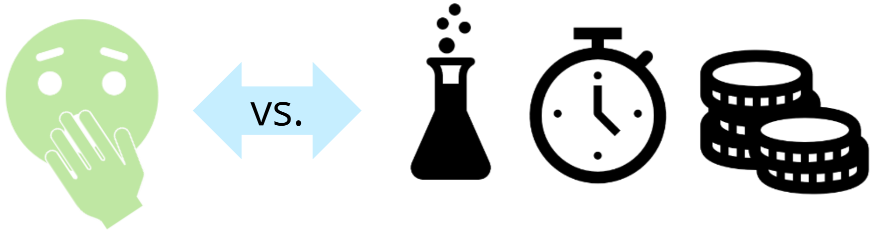
Challenges in chocolate cleaning

– **Chocolate consumption per year in Germany**



– **Empirical design of cleaning processes**

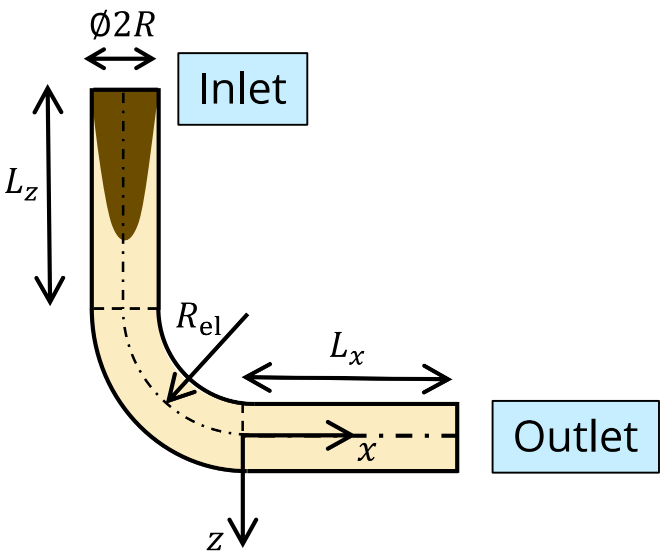


– **Improvement of cleaning processes through use of CFD simulation**

physical model | scalability | consumer safety | environment

Cleaning of chocolate

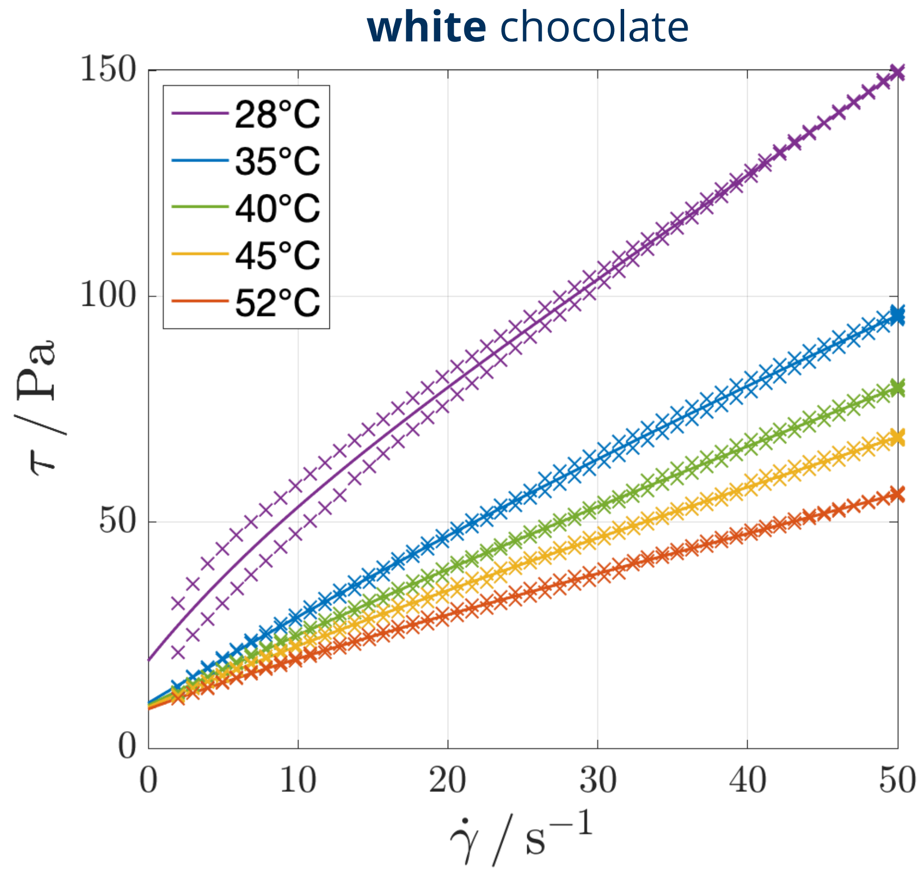
- Cleaning of chocolate from pipework by **flushing** displaced chocolate with displacing chocolate
  - White chocolate = **displaced**
  - Dark chocolate = **displacing**



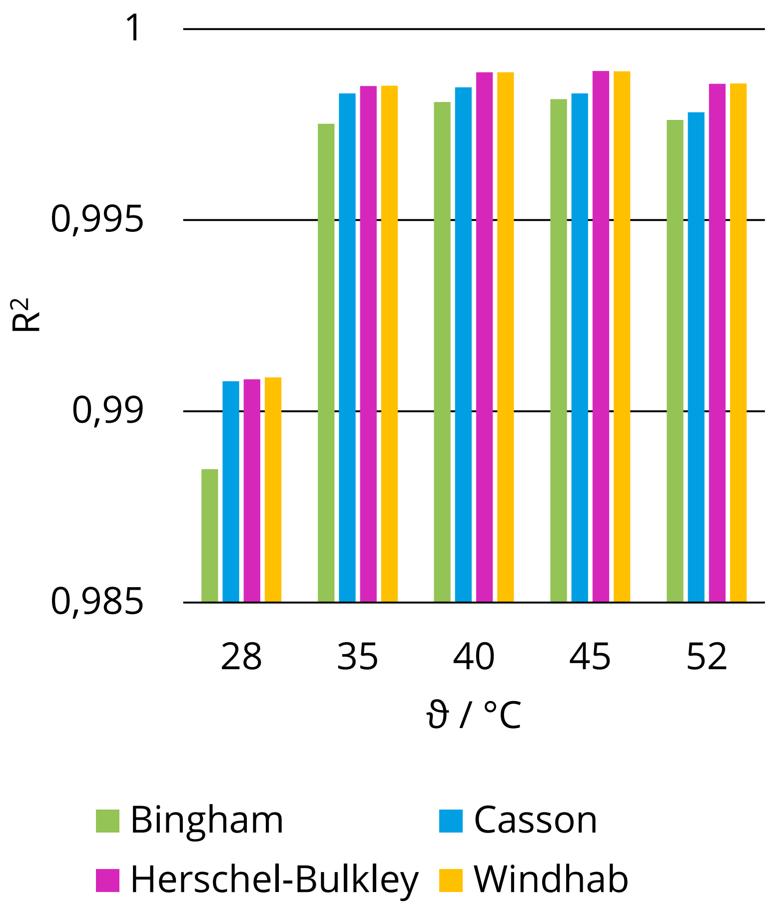
- **Modelling requirements** and structure of this presentation
  - Fluid properties
    - Rheology
    - Density
  - Chocolate specific phenomena
    - Wallslip
  - Numerical approach

Aspects of Modelling the Cleaning of Chocolate
Rheology

- **Measurement of rheological data** of white and dark chocolate for different temperatures
  - Fit of different models to experimental data
  - Comparison of the fit quality
- **Rheological models with yield stress**
  - Consideration of Bingham-, Casson, Herschel-Bulkley and Windhab Model



Aspects of Modelling the Cleaning of Chocolate
Rheology

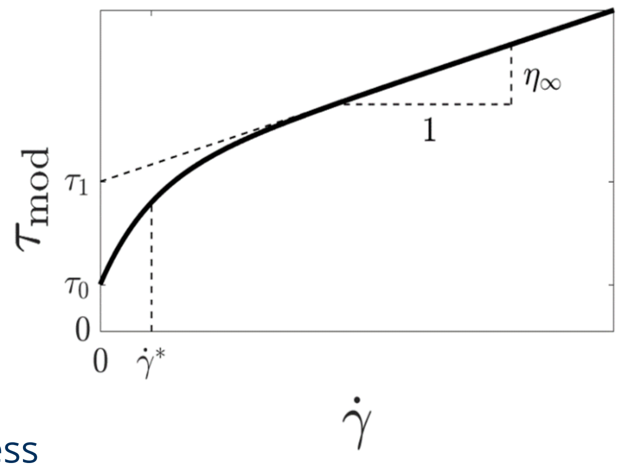


– **Windhab model**

$$\tau_{mod}(\dot{\gamma}) = \tau_0 + \eta_\infty\,\dot{\gamma} + (\tau_1 - \tau_0)\left(1 - e^{-\frac{\dot{\gamma}}{\dot{\gamma}^*}}\right)$$

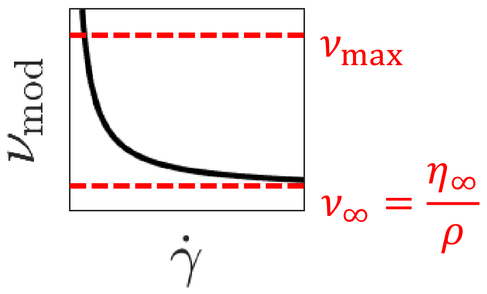
- Great fit for all chocolates, temperatures and shear rates
- Recommendation by IOCCC
- **Physical model parameters**

τ_0	yield stress
η_∞	viscosity for $\dot{\gamma} \to \infty$
τ_1	extrapolated yield stress
$\dot{\gamma}^*$	shear rate at 63% of $(\tau_1 - \tau_0)$



Aspects of Modelling the Cleaning of Chocolate
Rheology

– Implementation of **Windhab model** in OpenFOAM using the **kinematic viscosity**

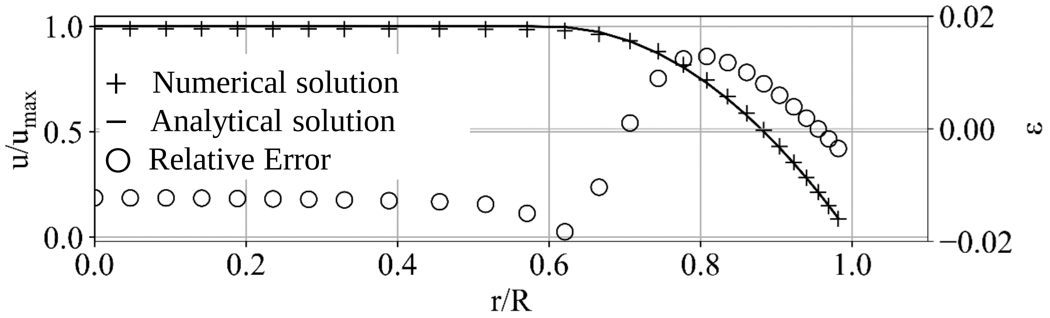


- **Limited by ν_{max}**, to avoid $\nu_{mod}(\dot{\gamma} \to 0) \to \infty$

$$\nu_{mod} = \max\left(\nu_{max}, \frac{\tau_{mod}(\dot{\gamma})}{\rho \min(SMALL, \dot{\gamma})}\right)$$

– **Verification** of the implementation

- **Maximum** relative error ε at **plug flow radius** and constant relative error in plug flow region
- Increasing $\frac{\nu_{max}}{\nu_\infty}$ leads to smaller errors but also longer computation times



Aspects of Modelling the Cleaning of Chocolate

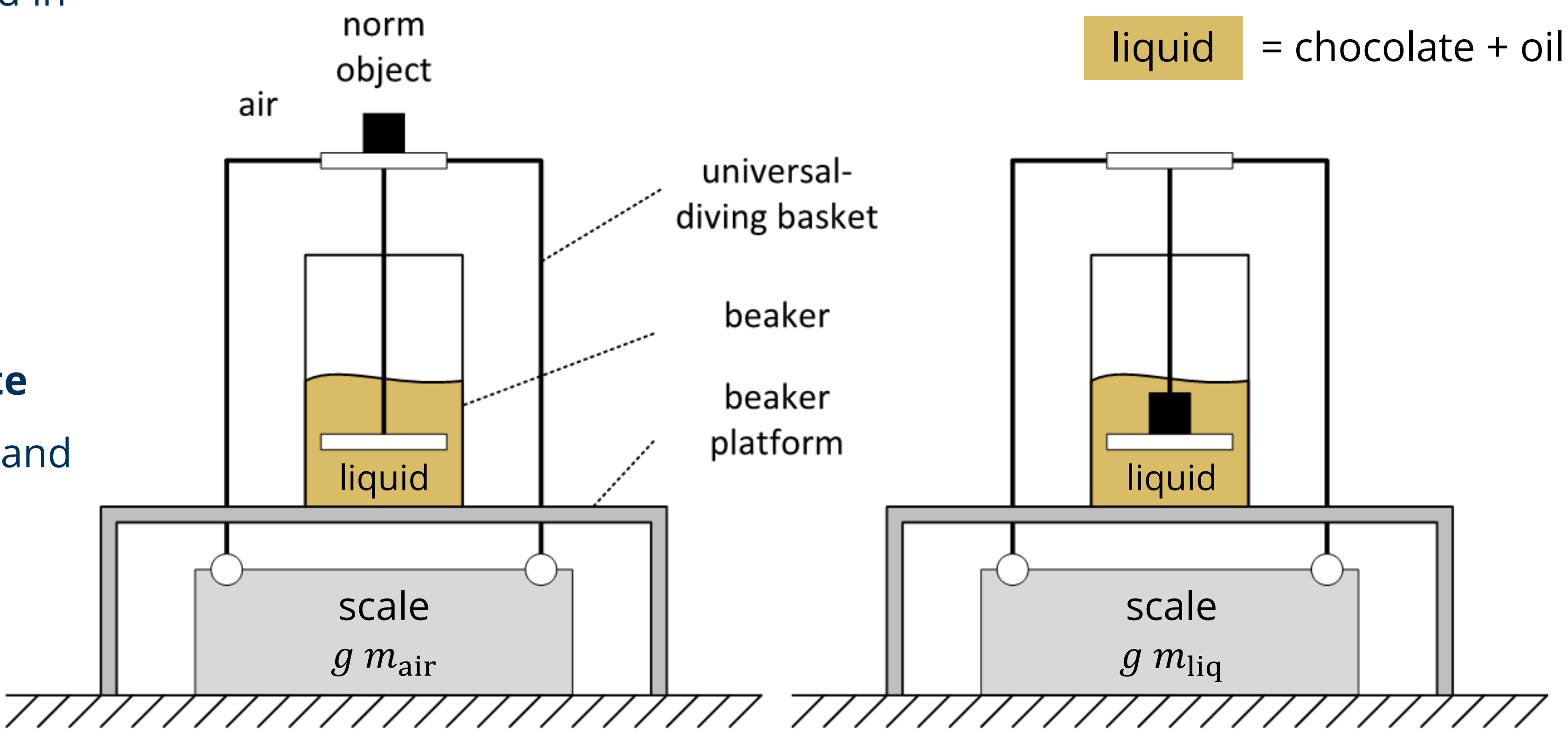
Density

- Norm object weighed in air and **liquid of unknown density**

$$\rho_{\mathrm{liq}} = \frac{m_{\mathrm{air}} - m_{\mathrm{liq}}}{V}$$

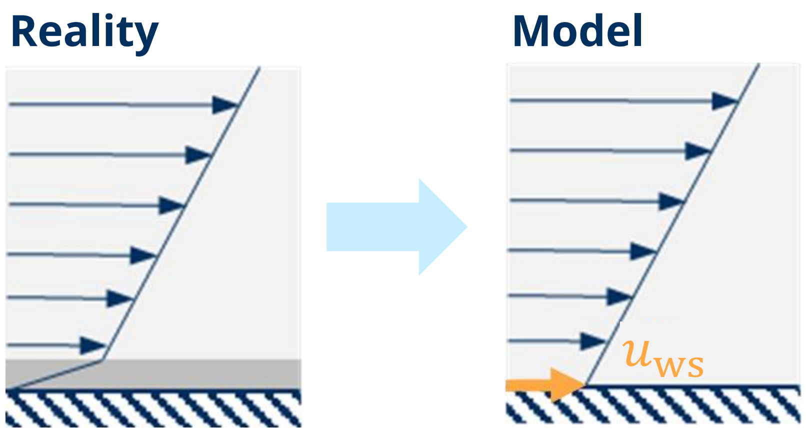
- **Density of chocolate** from liquids density and mass fraction of oil

$$\rho_c = \frac{m_c}{\frac{m_{\mathrm{liq}}}{\rho_{\mathrm{liq}}} - \frac{m_{\mathrm{oil}}}{\rho_{\mathrm{oil}}}}$$

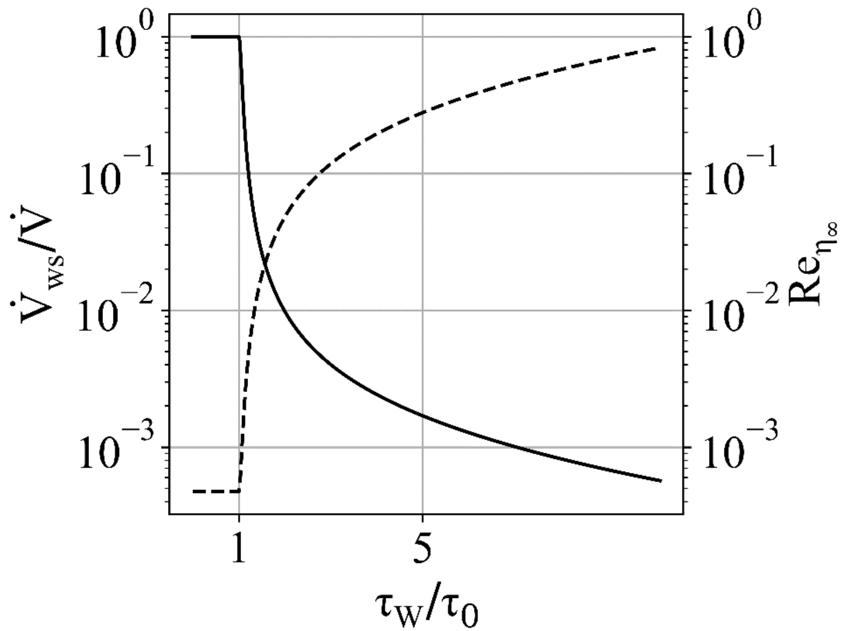


Aspects of Modelling the Cleaning of Chocolate
Wallslip

- **Chocolate = suspension** of cocoa, sugar and milk particles in cocoa butter
- **Segregation of particles** leads to different rheology
- Resolution of small layer with different rheology → high computational cost → model as wall slip velocity instead

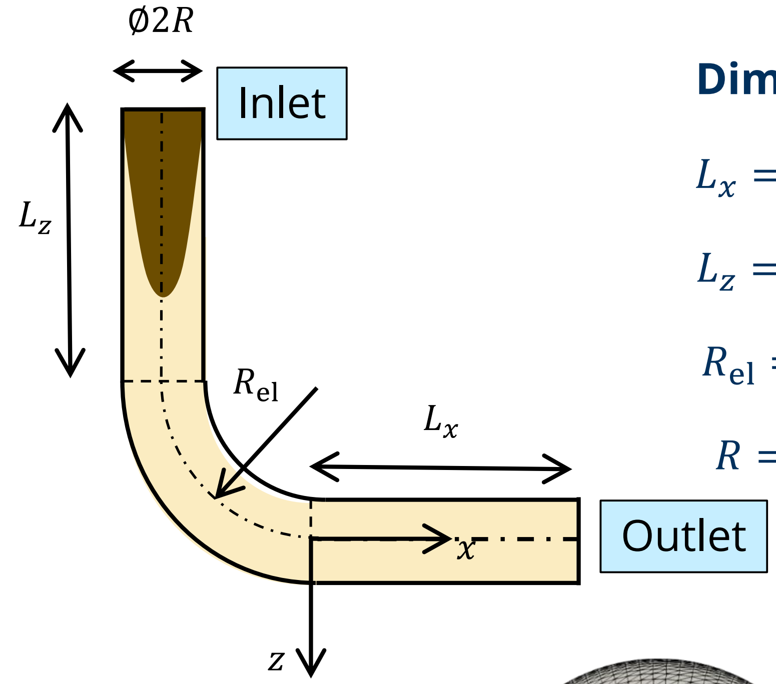


$$u_{ws} = \begin{cases} k_{ws}\tau_W, & \tau_W < \tau_0 \\ k_{ws}\tau_0, & \tau_0 \leq \tau_W \end{cases} \quad [1]$$



[1] E. Talansier et al.: Accurate methodology to determine slip velocity, yield stress and the constitutive relation for molten chocolate. *Journal of Food Engineering*, 244:220–227, 2019

Aspects of Modelling the Cleaning of Chocolate
Numerical model



Dimensions

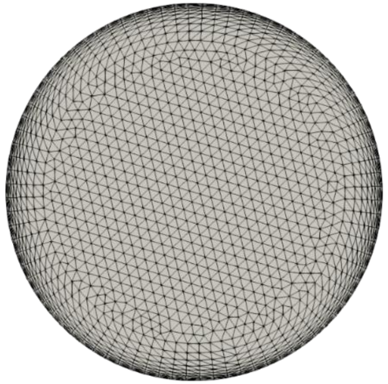
$L_x = 400$ mm

$L_z = 500$ mm

$R_{el} = 70$ mm

$R = 13$ mm

– **Numerical grid:**



– **MultiphaseInterFoam**

- Built-in **OpenFOAM** solver
- Two phases: white and dark chocolate, isothermal

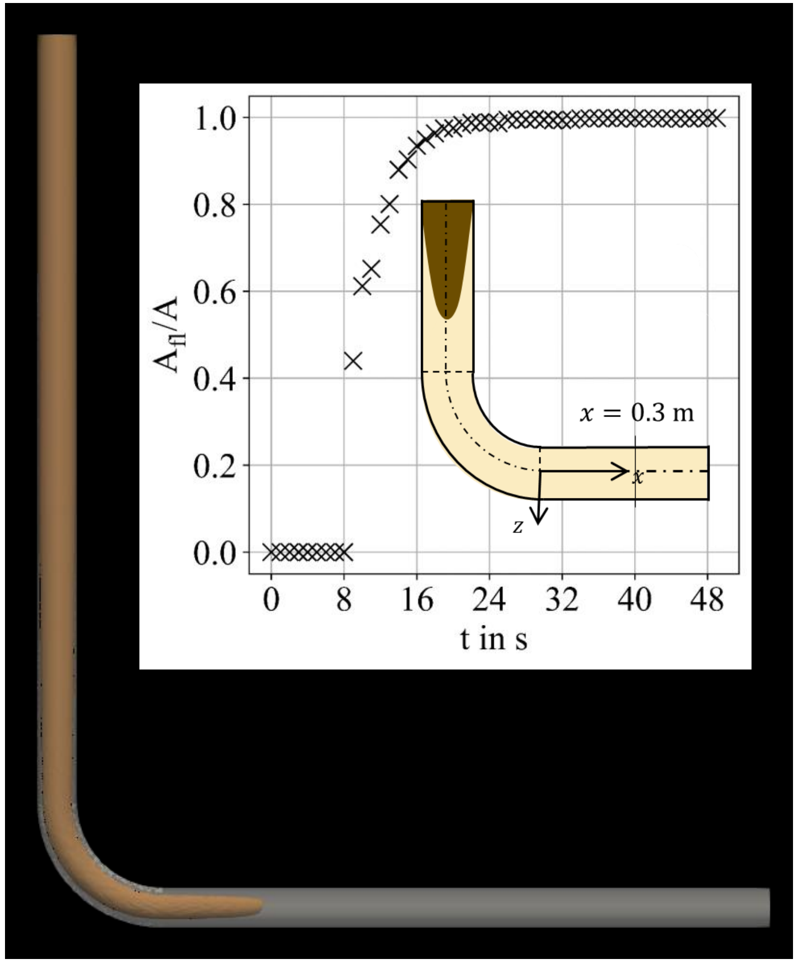
$$\frac{\partial u_j}{\partial x_j} = 0$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_j u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\tau_{ij})$$

$$\frac{\partial \alpha}{\partial t} + \frac{\partial(\alpha u_j)}{\partial x_j} = 0$$

- Geometry initally filled with white chocolate
- Inlet with dark chocolate

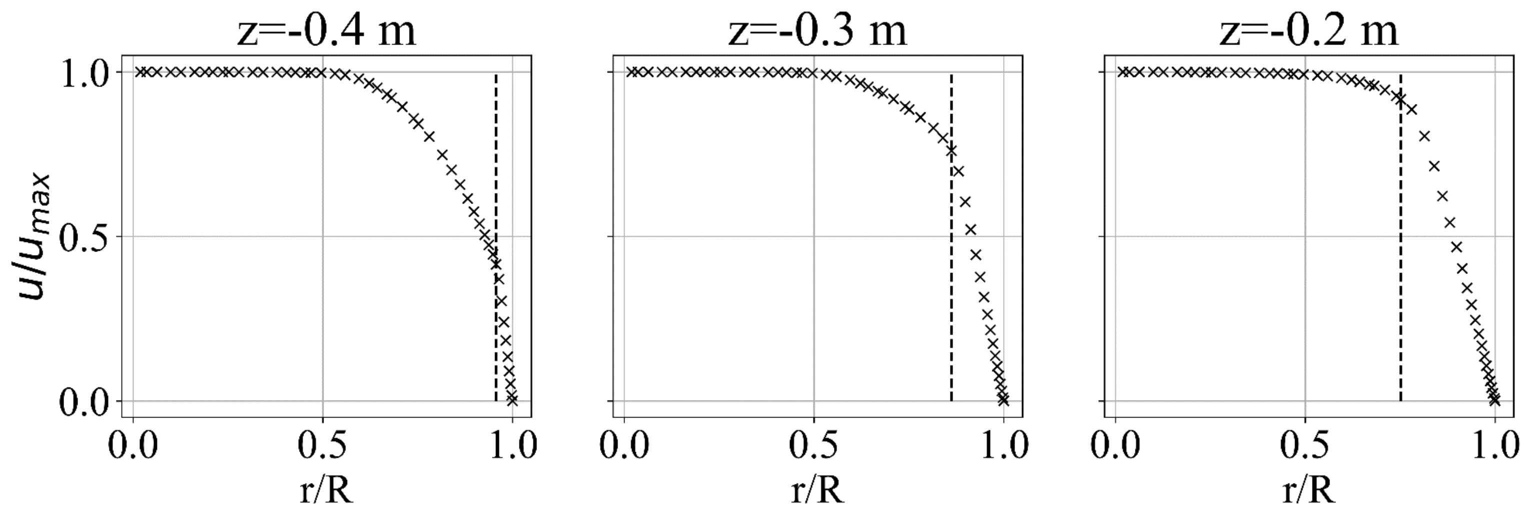
Cleaning simulation
Results

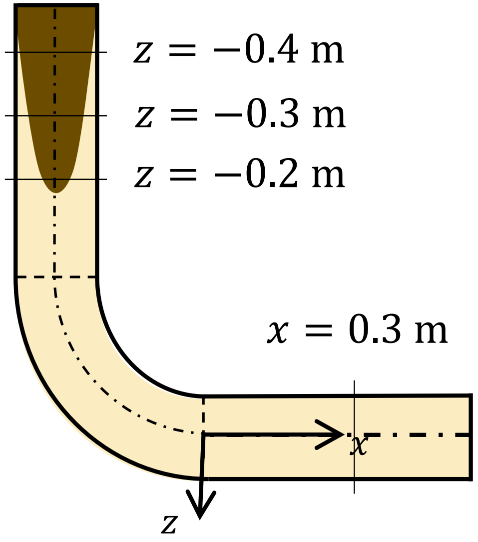


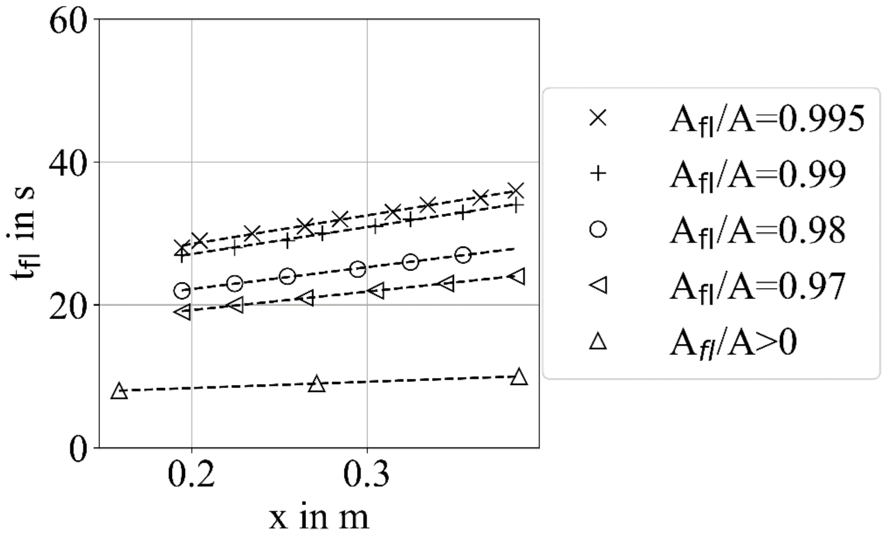
- **Cleaning starts** when front reaches cross section → $\boldsymbol{A_{fl} > 0}$
- Quick increase in cleaned cross-section due to **displacement of white chocolate in core region**
- Removal of remaining white chocolate layers on the walls slower
- Influence of elbow on distribution of chocolate downstream only visible for small ratio of A_{fl}/A

Cleaning simulation
Results

$t = 5$ s







- Velocity profile not differentiable at interface → may cause instability
- Longer flushing times for higher ratios of cleaned cross section necessary

Cleaning simulation
Conclusion and outlook

- **Rheology of chocolate** best described by Windhab model for different temperatures and shear rates
- Influence of **wallslip** negligible for high ratios of wall shear stress to yield stress
- Removal of chocolate from plug flow region quick, whereas removal from walls slow
- **Velocity profile not differentiable** near the interface for low ratios of flushed cross-section to overall cross-section
- Definition of a **cleanliness criterion**, e.g. minimal residual layer height